The perfect liquid and other highlights from RHIC

- Introduction to QCD and high energy heavy ion physics
- Soft/bulk results from the Relativistic Heavy Ion Collider
- Hard/Jets results from RHIC
  - Perspective for day 1 physics at LHC
The standard model particles and interactions

The perfect liquid and other highlights from RHIC

P. Christiansen (Lund)
QCD and hadronic matter

3 color charges (red, green, blue)

Hadrons have to be colorless

Baryons have all 3 colors

Mesons has a color and an anti-color

A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!
QCD Confinement and other Complications

- **QED vs QCD potential:**
  \[ V_{em} = -\frac{c}{r} \]
  \[ V_s = -\frac{c'}{r} + kr \]
  \[ c, c', k \text{ constants} \]

- Confining term arises due to the self-interaction property of the colour field. \( k \sim 1 \text{GeV/fm} \)

- QCD is for low energies non-perturbative \( \alpha_s \sim 1 \)
  - We know the theory but we cannot solve it!

- But at high energies (small distances \(<< 1 \text{ fm}\)) we can use perturbative QCD

\[ V_{em} = V_s = -\frac{c'}{r} + kr \]

- a) QED or QCD \((r < 1 \text{ fm})\)
- b) QCD \((r > 1 \text{ fm})\)
Numerical QCD at high temperatures: a gas of $q$ and $g$

$$\epsilon_{QCD} = \frac{\pi^2}{12} \left( 2 \times 8 + \frac{7}{4} \times 2 \times 2 \times 3 \times 3 \right) T^4$$

Gluon spin and color

(Anti+)quark spin, color and flavor ($u$, $d$, and $s$)

This suggests that the Quark Gluon Plasma should behave as a gas of quarks and gluons!
Deconfinement at large temperatures

At $T > 170$ MeV ($\varepsilon > 1$ GeV/fm$^3$) we expect a phase transition to a Quark Gluon Plasma (QGP).

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Current and future facilities

- Accelerators to produce the high energy beams
  - Relativistic Heavy Ion Collider at Brookhaven National Laboratory (outside New York)
  - Large Hadron Collider at CERN (near Geneva)

- Experiments to detect and reconstruct the final state particles
  - PHENIX and STAR at the Relativistic Heavy Ion Collider
  - ATLAS and ALICE at the Large Hadron Collider
Peripheral Event
From real-time Level 3 display.
Mid-Central Event
From real-time Level 3 display.
Central Event
From real-time Level 3 display.
Charged multiplicity $dN_{ch}/d\eta$ at mid-rapidity ($\eta \sim 0$) vs models

Model predictions at $\sqrt{s_{NN}} = 200\text{GeV}$

- HIJING ($dN_{ch}/d\eta$, $b<3\text{fm}$)
- HIJING+ZPC+ART ($b=0$)
- RQMD ($b=3\text{fm}$)
- UrQMD ($b<3\text{fm}$)
- VNI+UrQMD ($b<1\text{fm}$)
- HSD, VNI+HSD ($b<2\text{fm}$)
- NEXUS ($b<2\text{fm}$)
- DPM (Pb+Pb)
- DPMJET (Pb+Pb, 3%)
- SFM (5%)
- LEXUS (5%)
- EKRT saturation ($b=0$)
- Hydro+UrQMD ($b=0$)
- Fireball (~5%)
- MclV ($dN/d\eta$, $b=0$)

From the $dN/d\eta$ and transverse energy one can estimate the energy density and one finds:

$\varepsilon \sim 5\text{GeV/fm}^3 \gg 1\text{ GeV/fm}^3$ (numerical QCD critical $\varepsilon$)
With increasing energy/momentum resolution the number of (small-x) partons in a hadron/nucleus grows rapidly (dominate soft physics).

At the saturation scale $Q_s$ partons begin to overlap in the transverse area of the nucleus ($\sim A^{1/3}$), which prevents further growth of the parton density.

Color-Glass-Condensate: The many partons can be treated as semi-classical fields and the initial condition at RHIC can be calculated.
Pre-RHIC: $dN_{\text{charged}}/dy \ (\text{LHC}) = 8000!$

Day 1 physics will determine the role of the hard scale at LHC (very high energies)
Elliptic flow ($v_2$) unique to heavy ion collisions

Fourier decomposition:

$$dN/d\phi = 1 + 2 v_2 \cos(2 \Delta \phi)$$

Initial spatial anisotropy $\rightarrow$ Strong pressure gradients $\rightarrow$ $v_2$ Azimuthal anisotropy $\rightarrow$ Sensitivity to early expansion
Elliptic flow is close to ideal (non-viscous) hydrodynamics

The big surprise at RHIC was the agreement with hydro calculations and the large flow out to high pT (what is flowing there? Ask me:-)

This leaves little room for dramatic increases at LHC (by conventional hydro) < 25% increase.

Calculation by M. Luzum and P. Romatschke
AdS/CFT: The fluid is perfect!

- Anti-de-Sitter/Conformal Field Theories is a math trick
- Weakly coupled 5d super gravity is dual to QCD like theory
  - Strongly coupled
  - Conformal = no intrinsic scale = deconfinement = QGP
  - Infinite number of colors
  - No running coupling

Some big results from AdS/CFT
- Strongly coupled theories can have gas like energy densities
- Universal (for all forms of matter) lower bound on the viscosity to entropy density ratio: \( \eta/s \geq 1/(4\pi) \)

However, also some results disagree with experiment
- \( J/\Psi \) suppression as a function of \( p_T \)

Hope is to find dual QCD theory
Hard probes (pQCD): parton-parton interactions

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- quark

- hadrons

- leading particle
**Heavy Ion Jargon**

**Centrality (ex. for Au+Au):**

- The total energy is proportional to the participant.
- The number of parton-parton (quark-quark, quark-gluon, gluon-gluon) is proportional to the binary collisions.

**Example:**

- 6 participant
- 8 binary collisions
- (pp has 2 participant and 1 binary collision)
The nuclear modification factor for pions (1/2)

\[
R_{AA} = \frac{\frac{d^2 N^{AA}}{d p_T dy}}{\langle N_{bin} \rangle \frac{d^2 N^{NN}}{d p_T dy}}
\]
In central collisions we observe only 20% of the remnants from parton-parton collisions that we expected to observe!

What happens to the rest?

- They loose energy as they go through the high energy matter!
- This is the QCD signature we looked for!

But first let us consider other alternatives!
Could the binary scaling be wrong?

- Direct photons does not interact with final state hadronic matter!
- Direct photons shows no nuclear modification confirming binary scaling of hard processes!
Could it be an initial state effects? Au+Au vs d+Au

\[ R_{AA} \text{ vs } p_T \text{ [GeV/c]} \]

\[ R_{dAu} \text{ vs } p_T \text{ [GeV/c]} \]
Could it be an initial state effects? Au+Au vs d+Au
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Could it be an initial state effects? \( \text{Au+Au vs d+Au} \)

So it must be a final state effect!
The suppression is due to energy loss in the medium

Most jets are created back to back!

Adler et al., PRL90:082302 (2003), STAR

$4 < p_T^{(trig)} < 6 \text{ GeV/c}$  $p_T^{(assoc)} > 2 \text{ GeV/c}$
The suppression is due to energy loss in the medium

Most jets are created back to back!

A large energy loss requires a QCD interacting medium, i.e., a colored medium!

Adler et al., PRL90:082302 (2003), STAR

$4 < p_T^{\text{(trig)}} < 6 \text{ GeV/c}$  
$p_T^{\text{(assoc)}} > 2 \text{ GeV/c}$
Au+Au vs d+Au
Hot vs cold nuclear matter

No suppression seen in d+Au
→ Quarks and gluons loose/radiate energy as they interact with the colored quarks and gluons of the created matter.
This suggests that the quark gluon plasma has been discovered!

All 4 experiments published together in PRL:
Predictions for LHC

- Given that the experimental uncertainty probably will be ~0.1 the models are not that different (no punch through)
- Difficult to get much larger suppression without initial state effects due to the large unsuppressed surface

Compilation based on:
N Armesto et al 2008
J. Phys. G:
Nucl. Part. Phys.
35 054001
Taken from pbm.
Summary:

- Multiplicity dN/deta (dEt/dy, particle ratios, pT slopes) have established that we are above Tc
- Elliptic flow indicates that the medium interacts early – thermalized and collective (strongly interacting → sQGP)
- Jet quenching (light quarks) shows that jets interacts strongly with the medium → medium is colored
- Theoretical models fails to describe more than one effect at a time
- Day 1 measurements will complete the energy systematics of the bulk observables and jet quenching (and hopefully provide new unexpected results) in a regime where pQCD should work even better
Heavy ion collisions: The study of high energy QCD

The evolution of a heavy ion collision

- By colliding heavy ions it is possible to create a large ($\gg 1\text{fm}^3$) zone of hot and dense QCD matter
- Goal is to create and study the properties of the Quark Gluon Plasma
- Experimentally only the final state particles are observed, so the conclusions have to be inferred via models
“Measured” initial energy density

Bjorkens hydrodynamic formula for thermalized energy density in terms of measured transverse energy $E_T$

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{c\tau_0} \left( \frac{dE_T}{dy} \right)$$

PHENIX: Central Au Au yields

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2 \text{ GeV}$$

Formation(thermalization) time?
Identified particle ratios: $T$ and $\mu_B$ at freezeout

Particle ratios are well described by statistical models when decay from hadronic resonances are taken into account (only QCD input are the masses and decays).

The temperature is consistent with what we expect from Lattice QCD calculations for the transition temperature.

1. Generate hadrons with weights: $\exp(-(m + \mu_B)/T)$
2. Decay strongly
3. Compare to data
The QCD phase diagram with the measured $T$ and $\mu_B$.

- The statistical description of particle ratios is also good for lower energies: AGS and SPS. The temperature saturates at $T \sim 160$ MeV indicating that the system has crossed the phase boundary ($\rightarrow$ LHC prediction $\sim$ RHIC).

- But $p+p$ ratios can be described with a similar (canonical) formalism and $T$! So it is a hadronization attribute.

$T_{\text{lim}} = 161 \pm 4$ MeV

A. Andronic, P. Braun-Munzinger, J. Stachel, nucl-th/0511071

Because of the simple beam-energy systematics statistical models have predictive power!
Quantum Chromo Dynamics (QCD)

3 color charges (red, green, blue)

Hadrons have to be colorless

Baryons have all 3 colors

Mesons has a color and an anti-color

A single quark cannot be observed because it has color!

The quarks are confined inside the hadrons!
According to Bjorken:

\[ \varepsilon \approx \frac{1}{A_t} \frac{dN}{d\eta} \tau \frac{1}{<E_t>} \]

Estimate the energy density, assume \(<E_t>\sim 0.5\text{GeV},\)
Each nucleon-nucleon interaction produces on average a spherical symmetric distribution. Only by interacting elliptic flow is generated – hydrodynamic explanation.

Flow is strongest in the event plane because of the stronger matter gradient.


Relativistic hydrodynamic predicts elliptic flow

- The high energy medium interacts very strongly immediately after being formed
- Medium does not behave as a gas, but an almost perfect fluid!

Question: Where is QCD dynamics?
Hydrodynamic predicts $v_2$ (for $p_T<2\text{GeV/c}$)

- Mass difference comes from velocity/flow at freezeout
- $v_2$ at AGS and SPS is below hydro limit

Strong interactions are really strong => use hydro

Where is QCD dynamics?
What is flowing at high pT: The quarks are flowing!?  

Quark recombination into hadrons?  
Quark degrees of freedom?
Recombination at LHC(?)

- Normal particle production in jets is fragmentation
- Recombination allows the many partons from different quarks to recombine! \( p = \sum p_{\text{partons}} \) (Baryon \( p > \) Meson \( p \))
- \( N_{\text{jets}} \) increases at LHC => recombination region should change. Hwa and Yang (R.C. Hwa and C.B. Yang, Phys. Rev. Lett. 97, 042301 (2006).) predicts \( p/\pi^+ \approx 10 \) out to \( p_T \approx 20\text{GeV/c} \) with no associated jet structure!